Pollution Prevention and Risk Reduction for Chemical Processes

Module 1 (Part 2): Screening Chemicals for Environmental Risks

Background Reading:

D. T. Allen, Chapter 5 "Screening Chemicals for Environmental Risks"

By the end of this section you should:

- **be aware of the chemical and physical properties that govern a chemical's environmental partitioning and fate**
- **be able to estimate properties that govern environmental lifetimes**
- **be able to estimate properties that govern environmental exposures**
- **be able to perform simple exposure calculations**
- **be able to use principles of property estimation to design chemicals that minimize dose and toxicity**

Outline:

I. Estimating environmental persistance
II. Estimating ecosystem risks
III. Screening for environmental exposure
IV. Designing safer chemicals

I ESTIMATING ENVIRONMENTAL PERSISTENCE

Estimating atmospheric lifetimes

Chemicals emitted to the atmosphere undergo oxidation through a wide range of processes. One of the critical steps in these oxidations, particularly for organic compounds, is the rate of reaction with the hydroxyl radical. Hydroxyl radicals are extremely reactive species and can abstract hydrogen from saturated organics, add to double bonds or add to aromatic rings. Some of these reactions are shown below.

$$C_3H_8 + OH^{\cdot} \rightarrow CH_3\text{-}\overset{\cdot}{C}H\text{-}CH_3 + H_2O$$

oxidized products

Hydrogen abstraction from propane

$$C_3H_6 + OH^{\cdot} \rightarrow CH_3\text{-}\overset{\cdot}{C}H\text{-}CH_2\,OH$$

oxidized products

Hydroxyl radical addition to propylene

$$C_6H_6 + OH^{\cdot} \rightarrow C_6H_6\overset{\cdot}{}\text{-}OH$$

oxidized products

Hydroxyl radical addition to an aromatic ring

These reactions with hydroxyl radicals are often the first step in a series of reactions that lead to the oxidation of organics in the atmosphere. We will not examine the details of these pathways (the interested reader is referred to Seinfeld and Pandis, 1998), however, the relative rate at which hydroxyl radical reacts with a compound is a semi-quantitative indicator of how long the compound will persist in the atmosphere. For example, for the three reactions listed above (hydrogen abstraction from propane, addition to propene and addition to benzene), the rates of reaction are 1.2, 26., and $2.0*10^{12}$ cm^3/molecule-sec. respectively. This indicates that if reaction with hydroxyl radical is the dominant reaction pathway leading to oxidation in the atmosphere the rates of disappearance should be in the ratio 1.2 : 26 : 2. As shown in Example 5-8, this implies a ratio of atmospheric lifetimes of 106 hours : 5 hours : 64 hours

So, one method of assessing atmospheric lifetimes is to estimate rate of reaction with hydroxyl radical. Once again, group contribution methods are a viable approach. The mechanics of the method are similar to those discussed in Section 5.2. A molecule is divided into a collection of functional groups and each group makes a defined contribution to the overall rate of reaction. The method is slightly different than the methods discussed in Section 5.2, however, in that a single compound might have multiple rate parameters. Consider, for example, the reactions of propene. Hydroxyl radical can add to the double bond of propene. To estimate that rate constant we would note that the olefinic group in propene has the structure (CH_2=CH-), and based on the data in Table 5-13, the rate constant for hydroxyl radical addition would be $26.3*10^{12}$ cm^3/molecule-sec. But hydroxyl radical can also abstract a hydrogen from the terminal methyl group. This reaction, however, occurs much more slowly than the addition reaction. The group contribution for abstraction from a terminal methyl group is only $0.136 *10^{12}$ cm^3/molecule-sec. Thus, although propene can react via two pathways, only one is significant.

Identifying and estimating the rates of hydroxyl radical reactions with all of the functional groups in a molecule requires experience. In this chapter, we will limit our estimations to addition reactions for olefins, abstraction reactions and addition to aromatics.

Example 5.8
Using the rate of reaction of propene with the hydroxyl radical, estimate the atmospheric half-life of propylene.

Solution:

The rate of reaction implies a rate of disappearance of propene:

$$(d[C_{propene}]/dt) = k\,[OH\cdot]\,[C_{propene}]$$

where $[OH\cdot]$ is the concentration of the hydroxyl radical and $[C_{propene}]$ is the concentration of propene.

Assuming that the concentration of hydroxyl radical is steady state - the pseudosteady-state assumption (see, for example, Fogler, 1995) – leads to the following expression for the concentration of propene:

$$\ln ([C_{propene}]/[C_{0\text{-}propene}]) = -(k\,[OH\cdot])t$$

Where $[C_{0\text{-}propene}]$ is the initial concentration of propene, $(k\,[OH\cdot])$ is the rate constant multiplied by the steady state concentration of propene and t is the time of reaction.

Since $([C_{propene}]/[C_{0\text{-}propene}]) = \_$ when the concentration has reached one half of its original value, the half life is given by:

$$t_{\_} =$$

Assuming a value of $1.5*10^6$ molecules/cm^3 for the concentration of the hydroxyl radical (while $1.5*10^6$ molecules/cm^3 is a typical value – summertime concentrations in Houston can reach 10^7 molecules/cm^3) and a value of $26*10^{-12}$ cm^3/molecule-sec for k:

$$t_{\_} =$$

So, the half life for propene is the atmosphere is:

$$t_{\_} = \qquad\qquad \text{hr}$$

Repeating this calculation for propane and benzene, with reaction rates of 1.2 and $2.0*10^{-12}$ cm^3/molecule-sec, leads to atmospheric half lives of 106 and 64 hours, respectively.

Example 5-9
Estimate the atmospheric half life for octane.

Solution
Octane has the molecular structure CH_3- $(CH_2)_6$- CH_3. Since there are no aromatic, olefinic or acetyl groups, the primary reaction pathway will be hydrogen atom abstraction. Referring to the groups in Table 5-13, this structure can be represented by two - CH_3 groups and six -CH_2 groups. The abstraction rate is the sum of the contributions from each of these groups:

k = $*10^{-12}$ cm^3/molecule-sec

The experimental value is 8.68 $*10^{-12}$ cm^3/molecule-sec

Table 5-13. Group contributions to rate constants for hydrogen abstraction (Kwok and Atkinson, 1995)

Structural group	Group rate constant 10^{12} cm^3/molecule-sec
K(-CH_3)	0.136
K(-CH_2-)	0.934
K(>CH-)	1.94
K(>C<)	0
K(-OH)	0.14
K(-NH_2) (aliphatic)	21
K(-NH-) (aliphatic)	63
K(>N-) (aliphatic)	66
K(-SH) (aliphatic)	32.5
K(-S-)	1.7
K(-S-S-)	225
K(>N-NO)	0
K(>N-NO_2)	1.3
K(P(=O))	0
K(P(=S))	53

Table 5-14. Group contributions to rate constants for hydroxyl radical additions to olefins and acetylenes (Kwok and Atkinson, 1995)

Structural group	Group rate constant 10^{12} cm^3/molecule-sec
CH_2=CH-	26.3
CH_2=C<	51.4
-CH=CH- (cis-)	56.4
-CH=CH- (trans-)	64.0
-CH=C<	86.9
>C=C<	110.0
-CH=CH- (cyclic)	56.4
CH≡C-	7.0
-C≡C-	27.0

Table 5-15. Group contributions to rate constants for hydroxyl radical additions to aromatic rings (Kwok and Atkinson, 1995)

Structural group	Group rate constant 10^{12} cm^3/molecule-sec
Benzene	1.95
Pyrrole	110.
Furan	40.5
Thiofuran	9.53
Imidazole	36.0
Oxazole	9.1
Thiazole	1.4
Pyridine	0.37
1,3,5 triazine	0.15
Naphthalene	21.6
Quinoline	10.0
Anthracene	40.0
Phenanthrene	13.0
Benzofuran	37.3
Dibenzofuran	6.0
4 fused benzene rings	50.
5 fused benzene rings	50.
6 fused benzene rings	50.

Estimating overall biodegradability

In addition to all of the reactions that may occur with other chemicals in the atmosphere and in aqueous environments, we must also be concerned with the rate at which compounds are metabolized by living organisms. Developing an overall assessment of biodegradation will once again be difficult. Nevertheless, semi-quantitative assessments are possible. An ideal framework for estimating biodegradation would distinguish between the initial disappearance of the compound (primary biodegradation) and the complete conversion to parent compounds such as CO_2 and H_2O (ultimate biodegradation). It would also distinguish between aerobic (oxygen present) and anaerobic degradation. Unfortunately, primary and ultimate, aerobic and anaerobic biodegradation rates are available for only a small number of compounds. Therefore, the approach described in previous sections – statistical regression of measured environmental data to yield group contribution parameters – will not work because there are not enough biodegradation data. Nevertheless, it is extremely important to have a qualitative sense of the persistence of compounds in the environment and biodegradation is one of the most significant removal pathways for compounds in ambient environments. The pragmatic response to this problem has been to rely on estimations of biodegradation by expert panels. As described by Howard, et al. (1992) and Boethling, et al., (1994), expert panels can provide estimates of whether biodegradation occurs over hours, days, weeks, months or longer. These expert assessments can then be used as the basis for a group contribution method for biodegradation.

One such method (Boethling, et al., 1994) involves calculating an index that characterizes aerobic biodegradation rate in ambient environments.

$$I = 3.199 + a_1f_1 + a_2f_2 + \ldots\ldots + a_nf_n + a_mMW \quad \text{(Equation 5-23)}$$

Where I is an indicator of the aerobic biodegradation rate. A value of 1 indicates that the compound is expected to degrade over hours; a value of 2 corresponds to a lifetime of days; 3, 4 and 5 correspond to weeks, months, and longer, respectively. The parameter f_n is the number of groups of type n in the molecule, and a_n is the contributions of group n to degradation rate.

Table 5-16. Group contributions to ultimate aerobic biodegradation index (Boethling, et al., 1994)

Structural group	Group contribution (a_n)
Molecular weight	-0.00221
Functional groups	
Unsubstituted mono-, di-, or tri-aromatic ring	-0.586
Unsubstituted phenyl group	0.022
Aromatic acid (-COOH)	0.088
Linear 4 carbon terminal chain (-CH2-CH2-CH2-CH3)	0.298
Aliphatic acid (-COOH)	0.365
Alkyl substituent on a ring	-0.075
Aromatic F	-0.407
Aromatic I	-0.045
Tetra aromatic or larger ring	-0.799
Aromatic amine	-0.135
Aliphatic amine	0.024
Aliphatic Cl	-0.173
Aromatic Cl	-0.207
Aromatic -OH	0.056
Aliphatic -OH	0.160
Aliphatic ether	-0.0087
Aromatic ether	-0.058

Example 5-10
Estimate the biodegradation index for 1-propanol and diphenyl ether.

Solution
a.) 1-propanol has a molecular weight of 60 and contains an aliphatic -OH. Its biodegradation index is:

I = = 3.22

This implies a lifetime of weeks.

b.) diphenyl ether has a molecular weight of 170 and contains an aromatic ether and two mono-aromatic rings. Its biodegradation index is:

I = = 2.81

This implies a lifetime of weeks; literature data indicate a lifetime of months.

Summary

This section has provided a limited introduction to methods for estimating environmental persistence. The methods are generally specific to a particular environmental medium (air, water, or sediment/soil) and to particular reaction pathways (e.g., reaction with hydroxyl radical in the atmosphere or hydrolysis in aqueous environments). Often the methods will depend on local characteristics such as whether a water body is alkaline or acidic and the concentration of oxidizing species in the atmosphere. With all of these restrictions, the best that we can hope for from these methods in performing screening assessments is relative rankings of environmental persistence.

Section 5.3: Questions for Discussion

1. When we examine atmospheric oxidation, we monitor only the disappearance of the chemical of interest. Should we be concerned about the reaction products that are formed?
2. The methodologies presented in this chapter represent only a small fraction of possible environmental degradation pathways. How would you use these limited data to perform an overall assessment of environmental persistence?

II ESTIMATING ECOSYSTEM RISKS

A final set of structure activity relationships used in screening chemicals for environmental risks are used to assess ecosystem and human health impacts. In assessing ecosystem risk, the standard practice is to estimate toxicity for a variety of species. For example, mortality for daphnids, fish and guppies are frequently used in assessing ecosystem risk for premanufacture notices submitted under the Toxic Substances Control Act. The mortality for guppies can be correlated with octanol-water partition coefficient.

$$\text{Log } (1/LC_{50}) = 0.871 \log K_{ow} - 4.87 \quad \text{(Equation 5-24)}$$

where LC_{50} is the concentration that is lethal to 50% of the population over a 14 day exposure (expressed in μmol/L). This equation was developed using data from a variety of different compounds (including chlorobenzenes, chlorotoluenes, chloroalkanes, diethyl ether and acetone) (Konemann, 1981).

Other equations used in estimating ecosystem risk estimate are specific to certain compound classes. For example, toxicities for daphnids and fish can be estimated for more than 50 different compound classes. As examples, the correlations for acrylates are given below.

$$\text{Log } LC_{50} = 0.00886 - 0.51136 \log K_{ow} \quad \text{(Equation 5-25)}$$
(Daphnids, mortality after 48 hr exposure)

$$\text{Log } LC_{50} = -1.46 - 0.18 \log K_{ow} \quad \text{(Equation 5-26)}$$
(Fish, mortality after 96 hr exposure)

where LC_{50} is expressed in units of millimoles/L.

Example 5-11

Compare the fish, guppy and daphnid mortailities for an acrylate with log K_{ow} =1.28 (e.g. methyl methacylate)

Solution

The concentrations yielding 50% mortality are:

Guppies (14 day):	5690 μmol/L
Daphnids (48 hour):	0.226 millimoles/L = 226 μmol/L
Fish (96 hour):	0.020 millimoles/L = 20 μmol/L

Section 5.4: Questions for Discussion

1. Why are ecotoxicities evaluated for immature amphibians and similar biota?
2. Why are the lethal concentrations negatively correlated with the octanol water partition coefficient for these species?

III SCREENING FOR ENVIRONMENTAL EXPOSURE

The previous sections have described methods that can be used to estimate the properties that will govern a chemical's environmental partitioning and fate. This section will illustrate, through a few simple examples, how those properties can be employed to calculate exposures.

The primary routes for exposure to chemicals are inhalation, dermal contact and ingestion. Of these routes, inhalation is perhaps the simplest to evaluate quantitatively. Inhalation rates are multiplied by atmospheric concentration to determine exposure. The atmospheric concentration, of course, depends on emission rate, mixing rate and atmospheric lifetime. A simple case study is given in Example 5-10.

Example 5-10

Propylene is emitted at a rate of 10 metric tons per year into an airshed that has a volume of 10^4 cubic kilometers. Assume that the airshed has a residence time of one day and is well mixed. Calculate the steady state concentration of propylene, accounting for chemical reaction. Calculate an inhalation exposure for an adult, assuming an inhalation rate of 5 l/min.

Solution

a.) Perform a mass balance to calculate the steady state concentration of propylene:

$$\text{In} - \text{out} - \text{disappearance due to reaction} = 0$$

$$\text{In} = 10^4 \text{ kilogram/yr} = 7.5 * 10^{-3} \text{ gram moles/sec}$$
(based on a molecular weight of 42)

$$\text{Out} = \text{flow rate} * \text{steady state concentration of propylene}$$
$$= 10^4 \text{ cubic kilometers/day} * C_{\text{propylene, ss}} = 1.16*10^{14} \text{ cm}^3\text{/sec} * C_{\text{propylene, ss}}$$

$$\text{Disappearance due to reaction} = \text{Volume} * \text{rate}$$
(note that the rate of reaction for propylene was discussed in Section 5.2)
$$= 10^4 \text{ cubic kilometers} *26 *10^{-12} \text{ cm}^3\text{/molecule-sec} * 1.5*10^6 \text{ molecule/cm}^3 * C_{\text{propylene, ss}}$$
$$= 10^{19} \text{ cm}^3 \ *39 *10^{-6} \text{ /sec} * C_{\text{propylene, ss}}$$

$$C_{\text{propylene, ss}} = 1.5 * 10^{-17} \text{ moles/cm}^3$$

Assuming one mole of air occupies 22,400 cm^3 at ambient conditions,

$$C_{\text{propylene, ss}} = 3.3 * 10^{-13} \text{ moles propylene/mole air} = 0.3 \text{ ppt}$$

The exposure, assuming an inhalation rate of 5 L/min is :

$5000 * 1.5 * 10^{-17}$ moles/cm^3 = $7.5* 10^{-14}$ moles/min = $1.6 * 10^{-6}$ g/yr

Calculating atmospheric concentrations, in order to estimate inhalation rates, can be done relatively routinely. Often the models used to estimate atmospheric dispersion are far more sophisticated than the well mixed box model used in Example 5-10, but such dispersion models are widely available.

The problems associated with estimating environmental exposures via other routes become far more complex. Consider the relatively simple example of calculating exposure through drinking water of a chemical released to surface water. Assume that a chemical is released to a river upstream of the intake to a public drinking water treatment plant. To evaluate the exposure we would need to determine:

- **What fraction of the chemical was adsorbed by river sediments?**
- **What fraction of the chemical was volatilized to the atmosphere?**
- **What fraction of the chemical was taken up by living organisms?**
- **What fraction of the chemical was biodegraded or was lost through other reactions?**
- **What fraction of the chemical was removed by the treatment processes in the public water system?**

Thus, to estimate exposures will require information on the soil sorption coefficient, the vapor pressure, the water solubility, the bioconcentration factor, and the biodegradability of the compound, as well as river flow rates, surface area, sediment concentration and other parameters. A typical set of calculations is shown in Examples 5-11 through 5-13.

Example 5-11

Assume that a chemical, with a molecular weight of 150, is released at a rate of 300 kg/day to a river, 100 km upstream of the intake to a public water system. Estimate the initial partitioning of the chemical in the water, sediment and biota.

Data
Water solubility: 100 ppm
Soil sorption coefficient: 10,000
Organic solids concentration in suspended solids: 15 ppm
River flow rate: 500 million liters per day
Bioconcentration factor: 100,000
Biota loading: 100 g per 100 cubic meter

Solution

The ratio of concentrations in water, sediment and biota will be approximately:

1 :

Based on the river flow rate the total flow rates of water, sediment and biota are:

Water: (500 million liter/day * 1 kg/liter) = 500 million kg/day
Sediment: 500 million kg/day * 15 kg sediment/ million kg water = 750 kg sediment/day
Biota: 500 million kg/day * 0.1 kg biota/ million kg water = 50 kg biota/day

Performing a mass balance:

300 kg/day =

where (C_{water}) is the concentration in the water phase;

(C_{water}) =

This is well below the solubility of 100 ppm. The ratio of the mass in water, sediment and biota is:

Thus, although the concentrations are much higher in the biota and the sediment, more than 97% of the mass remains in the water phase.

Example 5-12

For the discharge described in Example 5-11, calculate the equilibrium vapor pressure above the river at the discharge point. Is volatilization from the river likely to be significant?

Data

Vapor pressure: 10^{-1} mm Hg

River flow rate: 500 million liters per day

River velocity: 0.5 m/sec

River width: 30 m

Solution

Assuming ideal behavior and the concentration determined in Example 5-11, the equilibrium vapor pressure should be:

To determine if the loss rate is significant, assume that a volume 10 m above the river reached this concentration for the length of the river's length to the public water system inlet (a total volume of 100,000 * 10 *30 m^3). Noting that 1 gram mole of air at standard conditions occupies 22.4 liters:

This is the mass required to saturate the atmosphere to a height of 10 m above the river for the 100 km length of the river. Compare this to the total discharge rate of 300 kg/day, and it is clear that volatilization will be negligible.

Example 5-13

For the discharge described in Examples 5-11 and 5-12, estimate what fraction of the initial discharge might still be in the water at the public water intake. If the treatment efficiency of this chemical in the water treatment plant is 95%, what would be the concentration in drinking water?

Data

Biodegradation half life: 300 hours

Solution

Based on a river velocity of 0.5 m/sec and a travel distance of 100 km, the transit time is 2.3 days. If the half life is 300 hours, the disappearance rate constant is (see Example 5-8);

$t_{\_}$ =

This can be used to calculate the ratio of final to initial concentration:

The concentration entering the treatment plant is 0.88 * 0.6 ppm.

The concentration in the drinking water is 0.01* 0.88 * 0.6 ppm = 5 ppb

Summary

The purpose of this section has been to illustrate how the properties evaluated in Sections 5.2 and 5.3 can be used to estimate exposures. Again, the models presented have been simple, demonstrating basic concepts of environmental partitioning, fate and exposure. More complex and accurate models are available, but are beyond the scope of these simple screening methods.

Section 5.5: Questions for Discussion

1. Why is most of the mass of the chemical considered in Example 5-11 in the water phase, while the concentrations in the sediment and biota phases are so high?
2. For Example 5-12, what vapor pressure would result in significant volatilization rates?
3. How would you develop an accurate estimate for volatilization rate in Example 5-12, if the losses were significant?

5.7 GENERAL PRINCIPLES FOR THE DESIGN OF SAFER CHEMICALS

The methods presented in sections 5.2 through 5.6 have focussed on assessing environmental risks. An alternative way to view these methods, however, is as design tools. Armed with a framework for evaluating environmental risks based on chemical structure, it is possible to systematically design chemical structures so that environmental risks are reduced. This section will present general principles and guidelines that can be used in designing safer chemicals and is adapted from material presented by DeVito (1996). More quantitative design problems are given in the problems at the end of this chapter.

In designing safer chemicals, it is useful to think about modifying properties so that

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Reducing dose

Converting an exposure (e.g. inhaling a chemical) into a dose (absorption by the blood through the lung membrane) generally involves the transport of a chemical across a membrane. The three primary membranes of interest are the lung - which controls uptake of chemicals that are inhaled, the skin – which controls the uptake of compounds from dermal exposures, and the gastrointestinal tract – which controls the uptake of chemicals that are ingested. Some of the characteristics of these membranes are listed in Table 5-17.

Table 5-17 Characteristics of membranes that control chemical uptake by the body (DeVito, 1996)

Membrane	*Surface area (m^2)*	*Thickness of absorption barrier (μm)*	*Blood flow (L/min)*
Skin	1.8	100-1000	0.5
Gastrointestinal tract	200	8-12	1.4
lung	140	0.2 – 0.4	5.8

In designing chemicals that will minimize human uptake, you may wish to consider properties such as volatility, octanol-water partition coefficient and water solubility. For high, medium and low values of each of these parameters, characterize whether exposure due to inhalation, ingestion, and dermal contact are likely to be important. For each of the properties, complete a Table like the one shown below.

Exposure route	*High water solubility*	*Moderate water solubility*	*Low water solubility*
Inhalation			
Ingestion	Potentially high uptake	Potentially high uptake	Low uptake due to poor mass transfer within g.i. tract
Dermal contact			

Section 5.7: Questions for Discussion

1. For what types of compounds would dermal, inhalation and ingestion exposures all be important?

Reducing toxicity

Designing safer chemicals by reducing toxicity requires a knowledge of the mechanisms by which compounds exert a toxic effect. While these mechanisms are not known in many cases, there are a few general mechanisms for toxicity that can be examined, leading to safer chemical designs.

One group of mechanisms associated with toxic effects are the reactions of electrophilic species with nucleophilic substituents of cellular macromolecules such as DNA, RNA, enzymes and protiens. Table 5-18 presents the possible effects of a number of common electrophiles.

Table 5-18. Examples of electrophilic substituents and the reactions they undergo with biological nucleophiles, and the resulting toxicity* (DeVito, 1996)

Electrophile	General Structure	Nucleophilic reaction	Toxic effect
Alkyl halides	R-X where X= Cl,Br,I,F	substitution	Various; e.g., cancer
α,β-unsaturated carbonyl and related groups	C=C-C=O C≡C-C=O C=C-C≡N	Michael addition	Various; e.g., cancer, mutations, hepatoxicity, nephrotoxicity, neurotoxicity, hematoxicity
γ-diketones	R_1-C(=O)-CH_2- CH_2-C(=O)-R_2	Schiff base formation	Neurotoxicity
Terminal epoxides	-CH- CH_2 O -O- CH_2-CH- CH_2 O	addition	Mutagenicity, testicular lesions
isocyanates	-N=C=O -N=C=S	addition	Cancer, mutagenicity, immunotoxicity

*the presence of these substituents in a substance does not automatically mean that the substance is or will be toxic. Other factors, such as bioavailability, and the presence of other substituents that may reduce the reactivity of these electrophiles can influence toxicity as well